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**NGC 3256: Kinematic anatomy of a merger**

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We have used the Australia Telescope Compact Array to image the neutral hydrogen in the merging system NGC 3256, to test the idea that globular clusters (GC's) form during the interactions and mergers of disk galaxies. We compare our observations with hydrodynamical numerical simulations, from the literature, to examine the hypothesis that the H I fragments with masses greater than  $10^{7\pm1}\mathcal{M}_{\odot}$  are sites of GC formation. We appear to have detected detached H I fragments in the vicinity of NGC 3256. These fragments, with masses  $\sim 10^7\mathcal{M}_{\odot}$ , may have little dark matter content which is also a characteristic of globular clusters, and so our observations support the hypothesis that globular clusters form in the type of interaction that resulted in NGC 3256.

*Subject headings:* galaxies: interactions — galaxies: starburst — globular clusters: general — ISM: HI

**1. Introduction**

NGC 3256 is a starburst galaxy in which 2 extended tidal tails reveal that an interaction between galaxies has occurred (see Fig. 1 and 2). It is included in the description by Toomre (1977) of the sequence of stages associated with merger of 2 disk galaxies. Kinematic information about

the gas in such a system could help answer questions such as whether mergers trigger starbursts, whether starbursts play a powerful role in active galactic nuclei, and whether mergers create gas condensations which could evolve into globular clusters (GC's ). Since NGC 3256 is not in a cooling flow group or cluster, and cooling flows are also suspected of playing a role in the formation of globular clusters, it is a key galaxy for studies which are tackling these questions.

Galaxy-galaxy interactions, which are a mechanism for driving reservoirs of hydrogen gas from the outer regions of the galaxies into the centre of the interacting system, trigger starbursts. This picture is consistent with the observation that CO emission, which indicates the presence of  $H_2$ , is strong and centrally concentrated in perturbed galaxies. Additionally galaxy-galaxy interactions could provide high pressure environments conducive to GC formation. For example, tidally shocked debris torn from the parent galaxies could have characteristics similar to the giant clouds which are thought to be proto-galactic building blocks. Bound clusters, such as GC, preferentially form in the dense, high pressure cores of such massive clouds (eg. Harris & Pudritz (1987), Elmegreen & Efremov (1997))

In the remainder of this section we will briefly discuss some aspects of nuclear activity and globular cluster formation in the context of the merging of two disk galaxies to form an elliptical-like galaxy. We also describe the known characteristics of the merging system NGC 3256.

Observations are presented in §2, §3 presents the results and §3.2 analyses the H I enhancements suspected of being detached gas fragments, §4 compares the global features evident in our data (described in §2) with some numerical models of galaxy mergers from the literature, and §5 reviews the characteristics which *suggest* that the detached fragments could be GC progenitors.

### 1.1. Globular Cluster Formation

It is now widely believed that the dominant giant ellipticals in clusters of galaxies are produced by mergers during the dynamical evolution of the cluster. The number of globular clusters per unit luminosity (the specific frequency  $S_N$  ) for these cluster giants is higher, by up to an order of magnitude, than for other ellipticals and spirals (Harris 1993). Based on observations of starburst activity and the large amounts of molecular gas in interacting galaxies, Schweizer (1988) argues that merger events provide an ideal environment for the formation of massive star clusters. Hence the  $S_N$  of an elliptical could be larger than the value derived from the sum of the GC's populations of the parent galaxies. The specific frequency issue is discussed in more detail in English & Freeman (2000; Paper I).

In Paper I, we focused on a scenario based on Kennicutt and Chu's (1988) demonstration that giant H II regions are probably the birthplaces of the young globular clusters (young populous clusters; YPC) as seen in the Magellanic Clouds. Our argument is that tidal disturbances provide a mechanism for enhancing star formation and hence generate giant H II regions in the disks of the parent galaxies and in the newly emerging galaxy. These ionised complexes in turn cradle YPC's

which are the young GC's. The new GC's are redistributed, along with the other components of the two disks involved, during subsequent changes in the potential field and hence the clusters in the elliptical have a roughly similar spatial distribution to the diffuse light distribution (as observed by Harris and Hanes 1987, for example).

Here we examine an extension of Searle & Zinn's (1978) proposal that globular cluster formation occurs in fragments around collapsing protogalaxies: gas fragments and also condensations in the tails and loops of merging systems experience tidally induced shocks, causing the formation of stellar subsystems. These fragments, together with the globular clusters that formed within them, subsequently become part of the final merged galaxy system. (We elaborate on this scenario in §5.) In this paper, we describe a search for such HI fragments around the merging system NGC 3256.

## 1.2. NGC 3256

NGC 3256 consists of two galaxies which are currently merging. It is very luminous in the far infra-red ( $L(8 - 1000\mu\text{m}) \sim 3 \times 10^{11} L_{\odot}$  (Sargent et al. 1989);  $L(10\mu\text{m}) \sim 3 \times 10^{10} L_{\odot}$  (Graham et al. 1987)), although not quite in the class of FIR ultra-luminous galaxies ( $\geq 10^{12} L_{\odot}$ ).

Its starburst nature is indicated by data over a wide wavelength range:

- The UV spectrum (Kinney et al. (1993)) has strong absorption features which indicate the presence of hot young stars;
- The [Fe II] and radio continuum data (Norris & Forbes (1995)) indicate that the radio emission is due to synchrotron emission from cosmic-ray electrons accelerated by supernovae whose progenitors were massive stars.
- Infrared observations by Graham et al. (1984), Doyon, Joseph, & Wright (1994), and Moorwood & Oliva (1994) indicate that the K band continuum emission and CO strength are due to red supergiants and that the high  $\text{Br}\gamma$  line emission is due to OB stars ionising H II regions.
- Smith & Kassim (1993) show that the spectrum of NGC 3256 closely resembles the archetypal starburst galaxy M 82 over the wavelength range from about 30 cm to 7500 Å.

We also note that although NGC 3256 has relatively few (7) giant H II regions, these regions are comparable in flux to about 36 30-Doradus-like H II regions (Paper I). Hence this system currently has a giant H II region formation rate 30 times that observed for typical Sc galaxies with  $M_B = -19.5$  (Kennicutt & Chu 1988). Additionally Moran et al. (1999) find that it is the most X-ray-luminous star-forming galaxy yet detected ( $L_{0.5-10\text{keV}} = 1.6 \times 10^{42} \text{ erg s}^{-1}$ ).

As discussed in §4, the appearance of the stellar tidal tails of NGC 3256 implies that the initial interaction event involved two similarly massive disk galaxies, and the luminosity of the stellar

envelope of this merging system implies that the end product will be an elliptical galaxy. At this stage of the merger process, the system appears to have two nuclei. One nucleus (northern) is visible in the optical continuum and  $H\alpha$ . The other nucleus, obscured in optical images, is present in the  $[\text{Fe II}]$  and radio continuum (3 and 6 cm) images of Norris & Forbes (1995). It is also evident in the K band images of Zenner & Lenzen (1993), Moorwood & Oliva (1994), and McGregor & Kim (1994). The upper image in Fig. 2 is composed of our  $H\alpha$  continuum-subtracted data (see Paper I), Norris & Forbes 3 cm data, and McGregor & Kim’s K-band data, which is also displayed in the lower image.

The identification of the two strong emission sources as the two nuclei of the parent galaxies is supported by the following arguments:

- In the radio continuum data, the fluxes and the spectral indices of these features are comparable (Norris & Forbes 1995).
- McGregor & Kim (1994) have found that the southern feature is 1.5 magnitudes fainter than the  $H\alpha$  nucleus in K, and its J-H and H-K colours are redder. This is consistent with the notion that the southern feature is a galaxy nucleus suffering foreground extinction.
- Using Chandra X-ray Observatory Lira et al. (2002) identify an X-ray object with each source, and using resolved NICMOS IR images, argue that the southern source is a nucleus with about 16 magnitudes of extinction.
- Although Graham et al. (1987) claim that the K-band surface brightness distribution can be described by an  $r^{1/4}$  profile out to a radius of 5 kpc, the surface brightness profile from the K image of Moorwood & Oliva (1994) is not that of a galaxy which has already relaxed sufficiently to be classified as an elliptical.
- Sargent et al. (1989) determined that the far infra-red luminosity per unit  $\text{H}_2$  mass is low relative to the FIR ultra-luminous galaxies. They argue that this value, together with the large extent of the CO emission and the unusually high mass of molecular gas, indicate a relatively early merger stage, in which the galaxy cores have not yet coalesced.

The near-infrared data also demonstrate that the starburst activity is extended. The two nuclei, the eastern  $H\alpha$  complex, and features in the northern  $H\alpha$  “arc” and in the southwest projection all have  $\text{Br}\gamma$  emission. The photometry of Graham et al. (1987) indicates that most of the IR luminosity arises outside the central kpc (i.e. the  $H\alpha$  nucleus) of the system.

In Paper I we examined that possibility that giant H II regions could be sites of GC formation. Our analysis suggests that the number of YPC’s produced is consistent with specific frequencies of GC’s estimated for elliptical merger remnants formed via mergers of spiral galaxies (Ashman & Zepf 1993). In the remainder of this paper we examine whether fragments of neutral hydrogen exist around NGC 3256 which could also be future sites of GC formation, without presuming a link between this scenario and the one in which GC’s are cradled in H II regions (§ 1.1).

## 2. Observations, Reductions, and Analysis

### 2.1. Single-Dish Observations

A single-dish HI profile (Fig. 3) was obtained using the ATNF’s Parkes Radio Telescope on March 2, 1991; at 21-cm the FWHM (full-width; half-maximum) of the beam is 15 arcmin. The system temperature was calibrated using Hydra A (43.5 Jy). We obtained two spectra with orthogonal polarisations, each with 512 frequency channels over 10 MHz bandwidth, for a total on-source integration time of 30 minutes and a reference integration time of 30 minutes. After fitting baselines to individual input scans, summing these to produce the spectra, and applying Hanning smoothing, the r.m.s. was 6 mJy and the velocity resolution was about  $8 \text{ km s}^{-1}$ .

### 2.2. Radio Synthesis Observations

Table 1 lists parameters associated with the spectral-line data cube described below.

The 21-cm HI synthesis data was acquired using three different antenna configurations of the Australia Telescope Compact Array (ATCA). The shortest baseline corresponded to an angular resolution of about 23 arcmin while the longest was about 7 arcsec with the choice of configurations optimized for angular scales larger than 30 arcsec. We observed the source on December 17, 1991, January 10, 1992, and June 18, 1992 for about 12, 10 and 7 hours respectively, with a secondary calibrator (PKS1104-445) observed for 5 minutes every 30 minutes. We used 512 channels over a bandwidth of 8 MHz centred on a heliocentric velocity of  $2770 \text{ km s}^{-1}$ , although these were later averaged in groups of five channels to produce a final velocity resolution of  $16.8 \text{ km s}^{-1}$ .

We processed the data using the Australia Telescope National Facility version of the AIPS reduction package. Each configuration was separately flux calibrated, adopting a flux density of 16.21 Jy (at 1407 MHz) for the primary calibrator source 1934-638. The continuum was subtracted in the U-V plane with UVLSF, which is a routine that fits to the real and imaginary parts of visibilities associated with channels designated as containing continuum-only emission. The data from the three observations were then shifted to a common velocity before they were combined to produce the UV data set. A subset of this set was mapped and cleaned using the AIPS task MX, to produce a spectral line cube of 33 image planes (each plane being a group of 5 channels) covering a velocity range of  $555 \text{ km s}^{-1}$ . Each plane has a typical rms noise of 0.9 mJy/beam (after primary beam correction), spans  $512 \times 512$  pixels, and the mean diameter of the synthesised beam 23 arcsec.

The background in each plane contains imaging artifacts consisting of randomly distributed rings that have the same scale as the innermost grating ring of the synthesised dirty beam. We did not self-calibrate the data since this technique is unreliable for ATCA observations on sources as weak and extended as NGC 3256.

A condensed version of this cube was made for display purposes; see Fig. 4 and §3.1.2. The cube was also smoothed for comparison with the Parkes single-dish data; see §3.1.1.

### 3. Results

#### 3.1. Global properties of NGC 3256

The integrated surface brightness map is shown Fig. 5; see the figure caption for details. While Fig. 5a was constructed after correcting for the primary beam, Fig. 5b was generated beforehand and indicates whether any features could be artifacts generated by this correction.

Fig. 1, which shows the relationship between H I emission (coloured red) and optical I-band emission (from Paper I), was produced at a time when only two configurations of the antenna array were available. The I band image (coloured green) is representative of the older stellar population and the continuum-subtracted ionised hydrogen image (coloured blue) displays star forming regions. This figure emphasizes a neutral hydrogen absorption feature which almost covers the spatial extent of the optical disk.

##### 3.1.1. 21-cm Flux Density

The single-dish spectrum is presented in Fig. 3; the integrated flux density from this spectrum is  $18 \pm 1 \text{ Jy km s}^{-1}$ . Since this is an underestimate of the HI emission, because it includes the central absorption feature, we measured the emission-only flux density from the spatially resolved ATCA data. Using the data in Fig. 5, we integrated the emission in annuli that were centred on the absorption feature of NGC 3256 and which had an annular width equal to the size of the major axis of the Parkes beam, and excluded the inner 26 arcsec of the galaxy from these measurements. We did not correct for inclination. The resulting integrated flux density of 21-cm emission is  $19 \text{ Jy km s}^{-1}$ , with an estimated 10% uncertainty.

As a further check, we compared the Parkes single-dish spectrum with a spectrum obtained by convolving the ATCA data with a Gaussian equivalent to the Parkes single dish beam. The two spectra are shown in Fig. 6.

From the ATCA data, we also measured the emission in each of the tails, excluding apparent fragments. To avoid the large velocity width features evident in the velocity curve (Fig. 7), we assumed the base of each tail resided beyond the 70 arcsec radius associated with the I band stellar envelope (see Paper I). This approach excluded emission which may belong to the east tail (i.e. the H I residing south of the absorption feature) and hence the value of  $4.6 \text{ Jy km s}^{-1}$  could be underestimated up to 30%. The value for the west tail,  $9.6 \text{ Jy km s}^{-1}$ , is larger but may also be

an underestimate. Therefore at least 75% of the H I emission comes from these extended features.

### 3.1.2. *Velocity Field*

Due to the peculiar morphology of NGC 3256, and the extinction in the centre, it is difficult to determine the centre of this system, its major axis and its inclination to the line of sight. Feast & Robertson (1978) used H $\alpha$  spectroscopy to determine a position angle of  $100^\circ$  for the major axis. They also adopt a kinematic minor axis which is offset from the visible nucleus by 4.5 arcsec to the west, with an associated systemic velocity of  $2820 \text{ km s}^{-1}$ . Our H $\alpha$  long slit spectrum, described in Paper I, with the slit at position angle  $90^\circ$ , also gives a systemic velocity of  $2820 (\pm 11 \text{ km s}^{-1})$  and a rotational velocity amplitude of about  $107 \pm 11 \text{ km s}^{-1}$ , uncorrected for inclination. This systemic velocity is associated with the disk which appears less disturbed by the merging activity than do the H I arms of the galaxy and the amplitude is significantly larger than the separation of the H I horns in the ATCA H I emission profile, Fig. 6 (which gives an H I systemic velocity estimate of  $2813 \text{ km s}^{-1}$ ).

Fig. 4 is a mosaic of contour plots of the HI emission, which has been corrected for primary beam effects. Each panel consists of two planes of the cube that have been summed together with a resultant velocity width per panel of about  $34 \text{ km s}^{-1}$  and a noise level of 1.3 mJy. We discuss the evident non-circular motions in § 3.2.

A map of intensity weighted velocity is shown in Fig. 8, and in Fig. 7 we present an H I position-velocity diagram at the same declination and position angle as the H $\alpha$  long slit spectrum. The velocity behaviour in H I shows overall rotation in the same sense as that described by the optical velocity map presented in Paper I.

### 3.1.3. *HI Absorption*

The neutral hydrogen gas distribution in the centre of the galaxy is characterised by a strong spatially-unresolved absorption feature. We fit an elliptical Gaussian, corresponding to the synthesised beam, to the absorption feature in each plane of the cube, to obtain an estimate of the minimum intensity in that velocity bin. We then used these values to construct the absorption profile in Fig. 9. The position of the absorption feature,  $10^{\text{h}} 27^{\text{m}} 51.3^{\text{s}} -43^\circ 54' 16''$  (J2000), remains constant throughout the velocity range.

The maximum absolute amplitude in absorption in one plane (at  $2834 \text{ km s}^{-1}$ ) is 38 mJy, which is only 6% of the continuum flux density of 0.621 Jy (Smith & Kassim 1993) at 20 cm. Thus either the gas in the disk is optically thin to HI absorption or else it has a small filling factor.

Our beam at 21 cm includes both the nuclei seen by Norris & Forbes (1995) in 3 & 6 cm continuum. The flux of the extended emission observed at 6 cm is about 280 mJy which, together

with the 621 mJy observed at 20 cm, implies a spectral index of -0.7, and suggests that there is no extended 21 cm flux which is unobserved at 6 cm. The two nuclei have fluxes of 34 and 31 mJy at 6 cm which implies a flux of about 77 mJy each in 20 cm continuum emission, and so the HI absorption could result from a relatively high (-0.3 – 0.5) optical depth in front of either or both of these nuclei, or could result from extended HI absorption covering all the extended continuum emission with a low optical depth. Our data has insufficient resolution to distinguish between these alternatives.

Various methods of displaying (e.g. Fig. 7 ) the cube indicate that absorption exists over the entire extent of the H I velocity range. Examination of channels before and after the 33 planes of the processed cube suggest that emission and absorption features exist outside the 555 km s<sup>-1</sup> velocity range we emphasised in our study.

### 3.1.4. Mass Estimates

For optically thin line emission from a single cloud, the column density is

$$N_{\text{HI}} = 1.823 \times 10^{18} \text{ cm}^{-2} \int T_{\text{spin}} \tau(v) dv$$

where the integral is equivalent to

$$\int T_{\text{brightness}}(v) dv$$

Integrating the flux over the solid angle of the galaxy, the amount of neutral hydrogen mass producing the H I emission is

$$\mathcal{M}_{\text{HIem}} = \left[ 23.6 v_{\text{systemic}}^2 h^{-2} \int_0^\infty S(v) dv \right] \mathcal{M}_\odot$$

The observed flux density integrated over the velocity range (19 Jy km s<sup>-1</sup>; see § 3.1.1) corresponds to an H I mass of  $3.5 \times 10^9 h^{-2} \mathcal{M}_\odot$  (with 75% in the tails; § 3.1.1).

For absorbing gas, however, observations are a combination of  $T_{\text{brightness}}$  and the temperature of the continuum source. Therefore to calculate the mass of this gas, we need to assume a spin temperature and a value of the optical depth ( $\tau$ ) in the column density equation. We estimate  $\tau$  by following the argument above in Section 3.1.3 and assuming that the 21-cm continuum follows the same spatial distribution as the 6-cm continuum image of Norris & Forbes (1995), but scaled to give a total 21-cm continuum flux of 621 mJy.

Using the resulting minimum and maximum surface brightnesses (B), we then determined  $\tau$  for each plane in the cube using

$$\tau(v) = -\ln \left[ 1 - \frac{B_{\text{absorption}}}{B_{\text{spin}} - B_{\text{continuum}}} \right]$$



and integrating over velocity in order to calculate  $N_{\text{HI}}$  in units of  $\text{atoms cm}^{-2}$ . To determine the mass detected by the ATCA we multiplied by the synthesized beam area and converted to solar masses. These two approaches to estimating the surface brightness give a mass range for the absorbing gas of  $\mathcal{M}_{\text{HIabs}} \simeq [0.2 - 1.0] \times 10^9 \text{ h}^{-2} \mathcal{M}_{\odot}$  for an adopted spin temperature of  $100^\circ\text{K}$ .

### 3.2. Observations of Globular Cluster Progenitor Candidates

#### 3.2.1. Spatially Distinct Fragments

We wish to assess whether there exist H I fragments in the cube possessing masses appropriate for GC progenitors. However we have not attempted to identify clumps embedded within the tails as distinct fragments. Nor have we attempted to distinguish foreground fragments from tail material with similar velocities. Therefore our sample of fragments is incomplete and preliminary.

Since the observations emphasized the extended scales ( $> 30 \text{ arcsec}$ ) of diffuse emission, we assume that the features which appear spatially distinct in Fig. 5 at the  $3 \sigma$  level (where  $\sigma = 1.3 \text{ mJy/beam}$ ) are candidate fragments. (At the  $2 \sigma$  level some features (like A4 and A5) appear attached to each other and to the tails, however they are clearly clumpy.) Some features could, in principle, be artifacts of the processing procedure. For example, A6, A10, A11 and A12 do not exist in Fig. 5b, before application of the primary beam correction. Therefore we assume they could be noise enhanced in Fig. 5a by the correction and do not include them in Table 2 which lists the sample of fragments that could be GC progenitor *candidates*.

In order to estimate the mass of these candidates we use the channel maps presented in Fig. 4 (described in § 3.1.2) along with ATCA spectra. To generate a spectrum of each fragment, the velocity plane in which the feature was most apparent was displayed. A polygon enclosing the feature was created and the flux density within this area was then measured in each plane of the cube. To be considered as a candidate H I fragment, a peak in such a spectrum needed to

- also exist in the associated panel of the mosaic in Fig. 4. In all but one case these features existed in a few consecutive velocity planes.
- have a morphology consistent with the shape of an isolated fragment in each velocity plane of Fig. 4. For example, it could not be associated with extended or diffuse features in any of the consecutive velocity planes.

If features listed in Table 2 are noise or are caused by the processing and analysis procedures, we would expect to see negative features with the same characteristics as the apparent emission objects. However we did not find any negative features that appeared in consecutive velocity planes in the profiles.

The integrated flux densities were measured from the spectra. For each fragment this involved

subtracting a background emission value per plane from the value of the fragment; this tabulated  $S(v)$  differs from  $S(v)$ -plus-background values by  $\sim 10\%$ . The integration included planes that bracketed the detections in velocity. For example, if the emission is mainly contained in one plane then we measured the flux density in that plane plus the planes on either side of the emission channel (and listed the number of planes as 3 in Table 2).

The integrated flux density and the velocity associated with the peak emission of the fragment candidate were used to calculate the H I mass via the  $\mathcal{M}_{\text{HIem}}$  formula given in § 3.1.4.

The FWHM velocity range was estimated by fitting a single Gaussian profile to the spectrum of each fragment (although A5 and A7 were not single peaked in velocity space). Since the main contribution to the uncertainty, listed in Table 2, is associated with our selection of the velocity planes in which the fragment exists, this rough approach was deemed adequate. In order to characterise the error in the FWHM velocity range, we examined the proportionality between the area under the Gaussian profile and the H I mass since the integrated intensity determined from the Gaussian fit should be consistent with the integrated flux density used to determine the H I mass of a fragment. The difference is less than 20% for the single peak fragments.

If we assume that the single peaked potential fragments are in virial equilibrium, and adopting a maximum radius, we can estimate an upper limit on their mass. The equilibrium mass is

$$M_{\text{virial}} = \frac{(\text{velocity dispersion})^2 \times (\text{mean radius})}{G}$$

We use (FWHM velocity / 2.354) for the velocity dispersion. Since the fragments are spatially unresolved, we use the mean radius (11.3 arcsec) of the synthesised beam as an upper limit on the mean radius for each potential fragment. Dividing the equilibrium mass estimate by the H I mass value gives an upper limit on the factor by which the total mass of the potential fragment, if it is in equilibrium, exceeds the amount of neutral hydrogen. Along with the FWHM, flux, and mass values, this ratio is listed in Table 2.

Our detection threshold is a few  $\times 10^6 \text{ h}^{-2} \mathcal{M}_{\odot}$  per plane. Since the fragments are measured over at least a few planes, the lowest mass object we are capable of measuring in this way is comparable to the lower mass limit associated with a globular cluster progenitor ( $\sim 10^{7\pm1} \text{ h}^{-2} \mathcal{M}_{\odot}$ ).

(A fragment appears in the last plane of the contour mosaic, Fig. 4, but not in the zeroth moment map, Fig. 5. If it is not a spurious noise feature, the mass estimated using the technique above is  $[3.9 \pm 0.8] \times 10^7 \text{ h}^{-2} \mathcal{M}_{\odot}$ .)

### 3.2.2. Fragments with Non-circular Velocities

Fig. 7 shows regions in H I that have a large velocity spread which we can associate with velocity anomalies in the optical velocity field presented in Paper I. However the distinct H $\alpha$

velocity features are usually near the disk of the galaxy and, due to the lower resolution of our H I data, not readily identifiable with isolated H I intensity features. We plan to investigate a variety of potential causes for the velocity anomalies using visualisation techniques once our data set has been merged with higher resolution baseline configurations.

## 4. A Tidal Tale

In this section we attempt to broadly sketch a possible history for NGC 3256 by comparing its observational characteristics with the interaction scenarios implied by generic hydrodynamical numerical models. Since the details of these models do not duplicate the details of our observations, this section highlights the need for a computational model designed to mimic this particular encounter.

### 4.1. Morphological and Star Formation Evolution During Galaxy-Galaxy Mergers: A Small Selection of Models

A lesson learned from the classic restricted 3-body study of dissipationless systems by Toomre & Toomre (1972) was that two parent galaxies of equal mass will produce equivalent counter-arms which grow into tails as the interaction progresses. Importantly, Toomre & Toomre also proposed that interactions would lead to the formation of elliptical galaxies via orbital decay. They also linked the observed prolific star formation in peculiar galaxy systems with galaxy-galaxy interactions, suggesting the violent mechanical agitation would bring a sudden supply of fresh fuel deep into the galaxy. NGC 3256, which is observed to have two similar stellar tails, a common envelope, and an enhanced star formation rate, could be a “snapshot” of two roughly equal-mass disk systems in the process of merging. Thus Toomre (1977) includes it in his observation-based schematic of a sequence of merger stages that begins with NGC 4038/9 (The Antennae).

The NGC 4038/9 close-encounter stage is preceded by an era of galaxy-galaxy interactions in which significant tidal friction causes the galaxies to orbit one another with a decreasing orbital period. Self-consistent modeling of the galaxies’ purely stellar component (Barnes 1992) demonstrates that the decay mechanism could be independent of any role gas may play. That is, tidal forces exerted by a companion galaxy on the other galaxy’s halo cause the latter galaxy’s orbital angular momentum (from its halo and subsequently its bulge) to be transferred into spin angular momentum in its own halo. Through repetition of this loss of orbital angular momentum, the galaxies’ orbits decay and, after the NGC 4038/9 stage, they fall back together in a rapid series of closer and closer pericentre passages until the parent galaxy cores coalesce. This can eventually produce a merger remnant with an  $r^{1/4}$  law profile.

Self-consistent hydrodynamical simulations by Mihos & Hernquist (e.g. 1994, 1996), which include processes in the ISM, show the star formation behaviour as two similar disk galaxies merge.

These numerical experiments illuminate both GC formation and nuclear activity. Mihos & Hernquist (e.g. 1996) find that the inner structure of galaxies, more than the orbital geometry, determines the formation and evolution of starbursts in merging galaxies since dense bulges act to stabilise the galaxies against gas inflow. Rather than forming bars, these disks acquire two-armed spiral features. The diffusely distributed gas later collects into a central cloud as the cores begin to merge. The resultant starburst is brief enough to be comparable to the age of observed starbursts, and intense enough to be descriptive of ultra-luminous galaxies. Additional sites of gas concentration, and hence possibly sites of enhanced star formation, are the condensations residing in the well-defined gaseous tidal tails.

## 4.2. Comparison of Observations of NGC 3256 with Numerical Models

### 4.2.1. *The Initial Encounter*

Lipari et al. (2000) interpret optical observations as suggesting NGC 3256 is the merger of 3 galaxies. However the extended H I is distributed into 2 broad tails and, although each of these has substructure, this is consistent with the scenario that NGC 3256 is mainly the product of two similarly massive parent galaxies involved in a prograde encounter. (The fact that the east tail has 60% less gas than the west tail could indicate that one of the parent galaxies was less gas-rich since its stellar mass could be similar in magnitude to the companion’s stellar mass.) The extrapolated IR luminosity of NGC 3256 also supports this scenario. It is only a factor of 3 less than that of the ultra-luminous category ( $\geq 10^{12} \mathcal{L}_{\odot}$ ) and it surpasses the  $10 \mu\text{m}$  luminosity of typical starbursts by an order of magnitude (Graham et al. 1984). Hence NGC 3256 is probably related to ultra-luminous starbursts. Ultra-luminous IRAS sources tend to have double tails and many have double nuclei (Sanders et al. 1988). If collisions of molecular gas can trigger events leading to FIR luminosities, then the optimal scenario for producing ultra-luminous starbursts involves mergers of similarly massive gas-rich galaxies. As well, the two radio continuum sources, which we identify with the original cores of NGC 3256’s parent galaxies in § 1.2, are approximately equivalent in luminosity (Norris & Forbes 1995) which may suggest that galaxies of similar mass were involved in the interaction.

The substantial spatial width of the H I tails of NGC 3256 suggests that our observational viewpoint is almost directly above the orbital plane of the interaction. The different shapes of the tails would then be due to the inclination of the parent galaxies’ disks with respect to the orbital plane, rather than due to extreme mass differences. If a galaxy’s spin is retrograde with respect to the encounter orbit, the formation of an extended tail is dampened. Hence the existence of two strong tails also implies that the spin of each galaxy was prograde with respect to the binary orbit.

#### 4.2.2. *The Current Encounter Stage*

It is possible that we are currently observing an epoch in which the parent galaxy cores have already merged and one of our designated nuclei may simply be a star formation enhancement. Then this would be a rather advanced merger stage and the kinematic coupling would suggest that the remnant system will retain a merger signature (kinematic and/or structural (Barnes 1992)) that reflects the characteristics of the close-encounter orbital geometry. However a number of observational and theoretical considerations, outlined below, indicate that NGC 3256 is experiencing the starburst which just precedes the final core collision when 2 gas rich galaxies with bulges merge.

- The common envelope shared by the nuclei in NGC 3256 indicates that this system has evolved beyond the close-encounter separation which designates the beginning of an on-going merger. Also enough time has passed to allow clumps to form in tidal tails, for enough gas to collect in the centre of each parent to induce starbursting, and for the galaxy nuclei to approach closely.
- The *global* sense of rotation of the ionised  $H\alpha$  gas and the neutral hydrogen gas implies that the gas in the inner region of the system ( $H\alpha$ ) is kinematically coupled to the gas in the outer region ( $H\text{ I}$ ); compare the velocity field in Paper I and Fig. 8 presented here. Therefore, although post-pericentre, the merger has not yet progressed to a stage where the inner region has lost a large fraction of its memory concerning its original angular and orbital momentum. However, the separation of 5 arcsec (Norris & Forbes 1995), or only about  $700\text{ h}^{-1}\text{ pc}$ , of the northern nucleus from the southern nucleus suggests that these are parent galaxy cores which are about to collide. It seems unlikely that the observed proximity of the cores is a projection effect since the inclination of the galaxy estimated by Feast & Robertson (1978) is only  $40^\circ$ .
- Norris & Forbes have shown that the supernova rate in each of the two components is about 0.3 per year, a rate which appears to be far too high for an extra-nuclear starburst region. (Since the eastern star forming feature at  $10^{\text{h}} 27^{\text{m}} 51.7 -43^\circ 54' 13.9''$  (J2000) does not have as strong radio continuum emission we do not assume it is another nucleus, as proposed by Lipari et al. (2000).)
- Lira et al. (2002) compare the spectral energy distributions of both nuclei with SEDs of starburst galaxies, QSOs, and low-luminosity AGN. The northern nucleus, the brightest X-ray source, is the heart of the nuclear starburst. However the southern nucleus has a flat SED between 1-10 microns, indicating that a low-luminosity AGN cannot be ruled out.
- The  $H\text{ I}$  absorption feature, spatially coincident with these nuclei, displays the full range of observed velocities in the system. There are a few scenarios which could cause this. For example, the velocity range could be evidence of a warp in the  $H\text{ I}$  disk and that we are viewing the galaxies' nuclei in projection. But again the morphology of the tails constrains

the warp to relatively low angles of inclination. Secondly, if we are indeed observing the orbital plane almost face-on, the velocity range could indicate that the absorbed H I gas resides in extended, inclined tidal loops and fragments (e.g. Hibbard & Mihos (1995)). However if gas were being funneled along these features into the central region of NGC 3256 all the velocities would be redshifted. Thirdly, and this is the more likely picture, the gas could be streaming. This is either because the 2 nuclei behave as a dipole or because there exists a structure such as a bar or an accretion ring (e.g. Koribalski et al. (1993)).

- Star formation activity is strong in NGC 3256, but its gas is not restricted to the central region. We observe an H II region formation rate of 60 times that observed for Sc galaxies occurring in a region that extends at least 70 arcsec range or about  $10 \text{ h}^{-1} \text{ kpc}$  (Paper I). Infra-red data mimics this distribution over about  $4 \text{ h}^{-1} \text{ kpc}$ ; most of the IR luminosity arises from outside the central kpc (Graham et al. 1987). Both the CO (Aalto et al. 1991) and H I emission are extended with most of the atomic hydrogen gas residing outside the disk (§ 3.1.1). (The H I mass in the centre, if it can be characterized by the gas in absorption, has an upper limit of about 30% of the spatially extended H I gas.) The onset of the current burst is relatively recent; using 2.5-40  $\mu\text{m}$  ISO SWS spectra, its age is estimated to be 10 to 20 Myr (Rigopoulou et al. 1996).

These observations are qualitatively consistent with the Mihos & Hernquist (1996) model in which the parent galaxies have bulges and the onset of enhanced star formation is delayed until it just precedes the final core collision. As this burst is occurring, the gas may still appear diffusely distributed and a small separation is also expected to exist between parent galaxy nuclei. We therefore adopt the picture that the designated nuclei are the cores of the progenitor galaxies and that the nuclei have yet to collide.

#### 4.2.3. Timescales

The proximity of the parent galaxy cores suggest that NGC 3256 has had more than one pericentre approach. However we estimate the time that has elapsed by assuming the gas, or “particles”, at the tip of the tails were torn from each parent galaxy during the pericentre associated with the current close-encounter stage. To estimate roughly the age of the tails, we assume the sum of the parent galaxies’ masses during the pericentre epoch is the same as that now observed within the optical envelope of the disk-like part of the system and the parent galaxies’ pericentre separation is taken to be very small. In Paper I we estimate the I band envelope mass within 70 arcsec of the  $\text{H}\alpha$  nucleus to be  $(2.5 \pm 0.5) \times 10^{10} \text{ h}^{-1} \mathcal{M}_{\odot}$ . From this mass, and the radius of the outer tip of the west tail ( $42 \text{ h}^{-1} \text{ kpc}$ ), the characteristic dynamical timescale is about 500 Myr.

To compare models to our data, we need to convert model unit quantities to physical values. For the total mass of one parent galaxy we adopt half of the I band envelope dynamical mass including its uncertainty since this provides an estimate of the H I mass that has been redistributed to the

tail during the interaction ( i.e.  $M_{\text{parent}} = 0.5 \times 3 \times 10^{10} h^{-1} \mathcal{M}_{\odot}$ ). The radius which contains half the mass of the parent galaxy can be estimated from our data using,

$$r_{1/2} = \frac{1}{2} \frac{G M_{\text{parent}}}{v_{\text{circ}}^2}$$

Assuming that before the interaction the parent galaxy had a rotational velocity which is comparable to the rotational velocity for the currently merging system, we used our estimate of  $107 \text{ km s}^{-1}$  (without any correction for the uncertain inclination).

In the Mihos & Hernquist (1994) models, unit mass and unit length are scaled to a specific galaxy using the parent galaxy’s total disk mass and the disk exponential scale length. A relationship between the radius at half-mass and the disk scale length,  $r_s$ , for an exponential disk can be determined numerically from

$$M(R) = 2\pi \int_0^R \Sigma_0 r e^{(-r/r_s)} dr$$

Setting  $M(R_{1/2}) = \frac{1}{2}M(\infty)$  gives

$$R_{1/2} = 1.7 r_s$$

Defining  $G \equiv 1$ , and using the length and mass calculated above, a unit time converts to about 10 Myr ( $h = 0.8$ ).

In Mihos & Hernquist (1994), the pericentre through to coalescence stage spans 50 model units, i.e. 500 Myr, which is comparable to our estimate of the time elapsed in NGC 3256. In their scenario for parent galaxies with dense bulges, a strongly peaked starburst begins about 40 Myr before the cores coalesce. Hence we consider this model and our data in adequate agreement.

#### 4.2.4. The Merger Remnant

As noted in § 1.2, the K luminosity profile is consistent with the notion that NGC 3256 will turn into an elliptical galaxy in the final merger state (Moorwood & Oliva 1994); this is independent of whether the parent galaxy cores have already coalesced or not. The notion of an elliptical remnant receives some support from the molecular-line survey by Casoli et al. (1992) that shows that the ISM of NGC 3256 is not simply that of a spiral galaxy which is very actively forming stars. It requires the the mixing of the gaseous components of the parent galaxies, which would occur if the original material in the galaxies were being redistributed into the  $r^{1/4}$  law associated with ellipticals.

The  $10 \mu\text{m}$  luminosity of the  $\text{H}\alpha$  nucleus rivals that of Seyfert galaxies (Graham et al. 1984), begging the question of whether an active nucleus currently contributes to the far-infrared luminosity. This seems unlikely for the northern core since observations do not provide substantial evidence of an active nucleus (IR: Moorwood & Oliva (1994) and Rigopoulou et al. (1996;ISO-SWS spectra); radio: Norris & Forbes (1995); X-ray: Moran et al. (1999) and Lira et al. (2002)). We note that the current starburst ( $\sim 3 \times 10^{11} L_{\odot}$  (Sargent et al. 1989)) could deplete a significant

amount of gas before this fuel can be funneled into the single dense concentration required to efficiently stoke an active galactic nucleus (Sanders et al. 1988). Additionally, although NGC 3256’s luminosity may increase as the parent galaxies’ nuclei more closely approach each other, the hydrodynamical simulations indicate that active nuclei are unnecessary for explaining ultra-luminous FIR emission (Mihos & Hernquist 1994). Lira et al. (2002) examine the AGN scenario in detail, concluding that the powerful X-ray emission could be driven solely by the current episode of star formation, which supports the starburst scenario. However they cannot rule out the existence of a *low-luminosity* AGN in the southern core.

## 5. Discussion

### 5.1. Globular Cluster Formation in Mergers

#### 5.1.1. *H I Fragments as Globular Cluster “Cradles”*

Some likely sites for globular cluster formation during mergers include detached H I fragments and the giant H II regions (see Paper I) and gas clumps that form in the tails of merging galaxies. Examples that dwarf-galaxy-sized fragments form in tidal features include the two condensations measured by Hibbard et al. (1994), in the tails of NGC 7252, with an H I mass of about  $10^8 \text{ h}^{-2} \mathcal{M}_\odot$ . Duc & Mirabel (1994) have also found two dwarf galaxies with masses on the order of  $10^9 \mathcal{M}_\odot$  in the tidal debris of Arp 105. Optical studies of NGC 3256 also are revealing stellar substructure in the tails (Knierman et al. 2001). However in our study of NGC 3256 we only designated spatially distinct clumps as GC progenitor candidates.

In this paper we focus on a GC formation scenario related to the Searle & Zinn (1978) idea that globular cluster formation occurs in fragments around collapsing protogalaxies. In the merging of a pair of galaxies, gas fragments associated with the tails and loops of the merging system form stellar subsystems (eg. Elmegreen (1997)) and papers therein). These fragments, together with the globular clusters that formed within them, subsequently become part of the final merged system. Simultaneously, galaxy interactions detach gas fragments from the parent galaxies. Evidence for detached fragments in merging systems comes from Hutchings’ (1989) study of IRAS galaxies. Fifty percent of his systems are interacting and many display weak subcomponents in their H I profiles. Such profile components are unlikely to be associated with the individual members of the interacting pair, and he suggests that they are due to material detached from the galaxies during the interactions.

Fragments which were not immediately captured by the emerging galaxy may evolve into the dwarf galaxies observed today, such as nucleated Blue Compact Dwarfs (BCD) and dwarf ellipticals (e.g. NGC 1705, (Freeman 1993; Meurer et al. 1992)) and dwarf spheroidals (Zinn 1993). The dwarf galaxy associated with the tidal tail of Arp 105 (Duc & Mirabel 1994) provides direct evidence for this type of scenario. If we assume that the star formation efficiency is  $\sim 10\%$ ,



then the masses of these dwarfs suggests that the minimum H I mass for GC formation in fragments is  $10^{7\pm1}\mathcal{M}_{\odot}$ . Hence the scenario is that fragments which are torn from interacting galaxies and which satisfy this mass limit will fall back towards the potential well of the remnant galaxy and experience tidally induced star formation. These episodes of starburst could be triggered by tidally generated gravitational instabilities (Elmegreen et al. 1993), by interactions between pairs of H I rich clouds (Brinks 1990), or by turbulent compression (Elmegreen & Efremov 1997). The clusters-to-be can be identified with the nuclei of the BCD dwarf galaxies (e.g. Freeman (1993)) or the progenitors of the GC systems observed in dSph’s (e.g. the Fornax Dwarf contains 5 GC’s) (Zinn 1993). The diffuse envelope surrounding the GC progenitors would be stripped off in the interaction, and the BCD nucleus survives as a GC when these “cradles” are subsequently accreted by the emerging elliptical.

From our preliminary analysis, NGC 3256 appears to have at least 3 spatially distinct H I fragments with H I masses which fulfill the minimum mass criterion; see Table 2. Inspection of smoothed Digitized Sky Survey images suggest Fragments A2 and A7 could have stellar components, but deeper optical images are needed to confirm this.

One could plan to test the plausibility of various GC formation scenarios by determining whether the observed numbers of GC progenitor *candidates* at every stage of the interaction-through-merging sequence are consistent with the statistical properties of small-scale features (eg. condensations of particles) in the hydrodynamical models of merging galaxies. These H I progenitor candidates in NGC 3256 could be examined for kinematic consistency with the models’ small-scale features.

The estimated virial mass of each fragment is similar to its H I mass. Caveats about this estimate include the short timescale in which the gas must virialize and the possibility that tides contribute to the observed velocity width. However if the gas is in equilibrium, then the fragments do not contain a substantial dark component and could be torn from a region of the parent galaxy which does not contain much dark matter, or at least that they are torn only from the gaseous component. This is not in contradiction with the observation that many dwarf galaxies contain a substantial fraction of dark matter (see Gallagher & Wyse (1994)). Among the local Group dwarfs (Mateo 1998) there are several examples of dwarf galaxies with globular-cluster-like  $M/L$  ratios ( $M/L \sim 2$ ).

### 5.1.2. *Enhanced Star Formation and Globular Cluster “Cradles”*

We may have expected to observe giant H II regions within the merger produced H I fragments if we also happened to be observing an epoch of enhanced star formation within the fragment. Elmegreen & Efremov (1997 and papers listed within) propose that stars form efficiently when the velocity dispersion is high since the binding energy per mass will also be high. The dispersion,  $c$ , within gas in a turbulent and virialized cloud is  $c \propto (PM^2)^{1/8}$ . Using typical values for  $c$  and mass

(M) for giant molecular clouds ( $3.8 \text{ km s}^{-1}$  and a few times  $10^5 \mathcal{M}_\odot$ ; Harris & Pudritz 1994) we can compare the pressure,  $P$ , in giant molecular clouds with the  $P$  in NGC 3256’s fragments. Using the average  $c$  for NGC 3256’s fragments (excluding A5 & A7) and a mass of  $10^7 \mathcal{M}_\odot$ , indicates a fragment’s  $P$  could be  $10^4$  times higher than that of a molecular cloud. This is a condition that Elmegreen & Efremov suggest will allow the formation of bound clusters containing massive stars.

A fragment’s appearance during the star formation episode which produces such clusters may be similar to that of an H II galaxy (Duc & Mirabel 1994) or a nucleating dwarf elliptical such as NGC 1705. However it would be serendipitous to observe an epoch of H II region formation in our few detached fragments because the lifetime of a giant H II region is only  $\sim 5$  Myr compared with the duration of the galaxy interaction ( $\sim 500$  Myr). Although we require sensitive optical observations in order to determine if the HI fragments contain stars, there is evidence that candidate stellar dwarfs are embedded in the tidal tails (Knierman et al. 2001). The origin of these tail substructures may be understood from the suggestion by Elmegreen et al. (1993) that, during galaxy interactions, clouds form by gravitational instabilities in the outer part of the disks; the interaction may also produce dense cores in molecular clouds and trigger the H II region formation by external compression (Elmegreen 1993). These clouds and their associated H II regions may be ejected from the disks and evolve into dwarf galaxies. The Elmegreen et al. (1993) star formation scenario could also link together the ideas that GC’s form in tidal fragments, presented in this paper, and that GC’s could form in giant H II regions, which we examined in Paper I.

### 5.1.3. *Specific Frequency and HI progenitors*

The  $S_N$  of globular clusters, which is the number of GC’s per unit absolute magnitude  $M_V = -15$  of galaxy luminosity, is such that (i.e. non-cD) elliptical galaxies have more than twice as many GC’s per unit stellar mass as spirals (Ashman and Zepf 1993). Thus in Paper I we calculate that between 40 and 80 GC’s need to be created if NGC 3256’s final state is to be identified with an elliptical remnant. We also show that, throughout the merger timescale, NGC 3256 will produce a sufficient number of H II region progenitors, as in the Kennicutt & Chu (1988) scenario, to create the required GC’s. However we also believe that GC’s with H I fragment progenitors, as in the Searle & Zinn scenario, contribute to some fraction of the GCS.

We are encouraged in this notion by the evidence that the progenitor of the globular cluster  $\omega$  Centauri evolved from a satellite galaxy. As well as displaying a flattened shape and rotation (van Leeuwen et al. 2000),  $\omega$  Cen’s heavy element abundance ratios, in the bimodal calcium abundance distribution, favour a scenario in which the ejecta from an earlier generation of stars enriched the next generation. Norris et al. (1996) suggest that in order for the proto-cluster to have not been disrupted by the Milky Way it had to evolve away from the central dense regions of the Galaxy. This condition can be satisfied if the progenitor was a halo gas fragment of  $10^8 \mathcal{M}_\odot$  that evolved into a satellite galaxy and was subsequently disrupted, as in the Searle and Zinn picture. Dinescu et al. (1999) elaborate on the disruptive final stage which removes the dwarf galaxy’s envelop

of stars, claiming from their kinematic studies that  $\omega$  Cen could have originated in a strongly retrograde satellite as massive as the Sagittarius dwarf spheroidal. We apply this scenario to the case of interacting galaxies by noting that early disruption can also be reduced if the gas fragment progenitor was originally far-flung tidal debris.

Since it is beyond the scope of this paper to analyze clumps embedded in the tidal tails and we lack knowledge about the longevity, and other characteristics, of our observed detached H I fragments, we cannot estimate the number of GC's that will form in the NGC 3256 merger by employing the analysis strategy used on H II regions in Paper I. Perhaps a hydrodynamical simulation specifically of the NGC 3256 interaction sequence would be illuminating. However, using a general interaction model can aid speculation, as the following example demonstrates.

In an interaction of 2 equal mass parent galaxies by Barnes & Hernquist (1996) numerous condensations occur in the tidal tails of the parent galaxies. These simulated clumps include gas since 10% percent of each galaxy's disk in the model consists of gas which is radiatively cooled until the temperature drops below  $10^4\text{K}$ . This non-gravitational process means that the model cannot readily be scaled to NGC 3256 and that the gas approximates the warm ISM rather than our cool fragments. Thus this model may be more relevant to the Elmegreen et al. (1993) scenario, mentioned at the end of the previous section, than to pure H I fragments. However, as a first approximation, let us assume that tail condensations are related to our fragments, and that their numbers and fragment masses do not change with size of the parent galaxies.

To make a generous estimate of the number of condensations that form, we need to assume that both galaxies are in prograde orbits and that their disks are not inclined with respect to the orbital plane. Then each might generate 2 dozen bound clumps, most forming shortly after the tails start to develop. Barnes & Hernquist (1996) state that most of these form in the outer region of the tails and many have high enough orbital periods to survive tidal disruption. Visual inspection of the number of clumps in the outer half of the tidal tails in their Fig. 20 suggests that up to 50% are still bound after 2 Gyr.

Although the bound clumps in the simulation originate with stellar overdensities which subsequently accumulate gas, the stellar component can be tidally dispersed while the more compact gas component resists disruption. Initially the condensations have an approximate mass range of  $10^{7-8}\mathcal{M}_\odot$ , 25% of which is gas. This suggests that about 20 condensations, once stripped of their stars, have the appropriate mass range for our scenario and may survive, thus potentially providing up to a half of the GC's required by specific frequency arguments in the case that NGC 3256 evolves into an elliptical remnant.

However to assume that these  $\sim 20$  gaseous proto-GC's are relevant to NGC 3256's interaction is optimistic. For example, only if the clump mass does not scale with parent galaxy size will all of the simulated gas condensations contain enough mass to be identified with the observed NGC 3256 fragments. In the model the number of condensations in the tail is this high only if the parent disks are not inclined to the orbital plane and the gas density in each dwarf is high because it

is collected from a thin ridge line in the tails. However NGC 3256’s parent galaxies are likely to have some inclination and we observe that the gas tails are broad. Further, to be identified with H I fragments described in our paper, some of the simulated condensations should have detached themselves from the stellar tidal features such as loops and tails within 500 Myr. So while these general models of Barnes & Hernquist (1996) support in principle the formation of GC’s from tidal debris, clearly more fitting simulations are required. These and multi-wavelength observations of the characteristics of gas condensations and fragments are required before we can calculate a realistic contribution of tidal debris dwarfs to the GCS of merger remnants like NGC 3256.

## 6. Conclusions

Our H I observations of NGC 3256

- Confirm that this system was mainly formed as the result of a prograde encounter between two similarly-sized gas-rich spirals. The cores of these parent galaxies appear to be on the point of coalescing. We estimate that the encounter that produced the tidal tails occurred 500 Myr ago.
- Show  $[3.5 \text{ to } 4] \times 10^9 \text{ h}^{-2} \mathcal{M}_{\odot}$  of neutral hydrogen gas is providing fuel for highly IR-luminous starburst activity. However this gas is distributed over several kpc, despite the conventional assumption that ultraluminous galaxies are powered by a compact circum-nuclear starburst. Also the H I in the central region has not yet been depleted by the activity. An absorption feature, which displays the same velocity range as the rotation curve, is consistent with streaming gas.
- Display a number of apparently isolated fragments. The H I masses of these ( $\geq 10^{7\pm1} \mathcal{M}_{\odot}$ ) suggest they could be progenitors of globular clusters. These may pass through a dwarf galaxy stage during their evolution. The equilibrium and H I masses of these fragments are similar which suggests they were torn from a portion of the system which does not have dark matter. The absence of dark matter is also a characteristic of globular clusters.

Both lower and higher spatial resolution ATCA observations of NGC 3256 in H I spectral-line mode have been acquired from which we examine the velocity anomalies and morphology of the inner region of this system. When these data are merged with the set presented here, the resolved absorption feature will allow us to examine whether the gas is streaming between nuclei, along a bar, or in an accretion torus. These data will also allow us to compensate for the incompleteness of our H I fragment sample and assess whether stellar enhancements in optical data are associated with these fragments.

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Fig. 1.— An overlay of 3 different data sets of NGC 3256. Data from the neutral hydrogen spectral line cube is presented as an intensity zeroth moment map in red. This data was acquired with the Australia Telescope Compact Array (ATCA) and consists of only 2 antenna baseline-configurations. The I band (coloured green) and ionised hydrogen (coloured blue) images were acquired with the 1 metre telescope at Siding Spring Observatories. Note where the radio and optical data overlap the false colours mix to form yellow. North is to the left and east to the bottom. Fig. 8 indicates the scale associated with the ATCA data.

Fig. 2.— The Southern Source in NGC 3256. The lower panel is McGregor & Kim’s (1994) K image acquired with the CASPIR detector on the 2.3m telescope at Siding Spring Observatory. The upper image consists of 3 different data sets. The images have been shifted to the coordinates of our H $\alpha$  CCD image (see Paper I) and overlayed using IRAF’s **rgbsun** task. McGregor’s K image is designated red, our continuum-subtracted H $\alpha$  data is assigned blue, and the 3cm continuum emission observed by Norris & Forbes (1995) green. Where the data sets overlap the colours add together. For example, the prevalence of the IR emission makes the H II regions appear magenta and the 3 data sets coincide on the northern nucleus rendering it white. Since the southern “nucleus” is obscured in H $\alpha$  it appears bright yellow. The circles mark the peak and the tip, i.e. edge, of the extended  $^{12}\text{CO}$  J = 2 – 1 line emission observed by Aalto et al. (1991); their radius of 5 arcsec corresponds to the SEST pointing error. (The CO tip occurs at the position of the HII region designated B4 in the photometry figure presented in Paper I.) We thank McGregor, and Norris & Forbes, and Aalto et al. for permitting us to reproduce their data in this format.

Fig. 3.— The Parkes Profile of 21-cm emission in NGC 3256. The emission combined with the absorption of the background continuum sources produce the Parkes flux density values displayed by the solid-line. The heliocentric velocities on the bottom axis were calculated using the radio definition of velocity while those on the top are calculated using the optical definition. The dashed-line displays the flux density values of the ATCA data once it has been multiplied by a Gaussian with a FWHM of 15 arcmin in order to mimic the Parkes data (see § 3.1.1).

Fig. 4.— HI contour mosaic. Pairs of planes from the 33 plane 21-cm spectral line cube have been summed resulting in a velocity width of about  $34 \text{ km s}^{-1}$  per plane. The r.m.s. noise in each plane is 1.3 mJy; and the contour range, in  $\sigma$  levels, is -60,-50,-30,-15,-8,-6,-5,-4, -3,3,4,5,6,8,10,12. The beam size is displayed in the top lefthand corner of the first panel.

Fig. 5.— The distribution of H I in NGC 3256. An integrated surface brightness (zeroth moment) map of the primary beam corrected ATCA H I cube. The data cube was smoothed in the spatial direction (on the scale of the width of the synthesised beam) and smoothed in the velocity direction (over 5 planes). The calculations do not use intensities between -1.5 sigma and 1.5 sigma from the background since these intensities were taken to be noise. As another conservative measure we subsequently *blanked* features which did not appear simultaneously in the zeroth, first, and second moment maps and which were much smaller than the synthesised beam. The integration occurs over a velocity range of  $555 \text{ km s}^{-1}$ . The labelled spatially separated fragments also appear



in a  $1.5\sigma$  moment map from the cube before the primary beam correction has been applied; for the characteristics of the fragments see Table 2. The figure on the right is the same except calculated using the ATCA H I cube before applying the primary beam correction.

Fig. 6.— The ATCA Profile of 21-cm emission in NGC 3256. The solid-line spectrum does not include measurements of the absorption feature. The error bars reflect the uncertainty in the measurement due to the r.m.s. and the use of different display parameters. The dashed-line spectrum portrays ATCA data as Parkes single-dish telescope measurements (see § 3.1.1). The heliocentric velocity has been calculated using the optical definition.

Fig. 7.— HI velocity curve. A position-velocity plot of the ATCA cube along the same position angle ( $90^\circ$  and at the same declination as the ionised hydrogen velocity curve presented in Paper I.

Fig. 8.— The H I velocity field in NGC 3256. Artifacts suspected of being noise have been blanked out in this mean velocity (first moment) map of the primary beam corrected ATCA 21-cm spectral line cube. Values between  $-0.0013$  and  $0.0013$  Jy (i.e.  $\sim 1.5\sigma$ ) were not used in the moment analysis. The mean diameter of the synthesised beam is 23 arcsec. The full colour range was chosen to maintain the convention ‘red corresponds to redshift and blue corresponds to blueshift’. To create the intervening velocity range, the red and blue extremum were blended together. (Note: The saturation of the red was set such that it was dull and the blue chosen was a ‘warm’, bright blue. Hence the red colour, in terms of human visual perception, appears to recede and the blue colour visually jumps forward, supporting the kinematic meaning of redshift and blueshift.)

Fig. 9.— The ATCA Profile of the Absorption Feature in NGC 3256. The flux densities were determined using by fitting a Gaussian to the unresolved absorption feature in each plane of the cube. The uncertainty is dominated by the error in this fit.